# Measurements of the Mass and Width of the $\eta_c$ Meson and of an $\eta_c(2S)$ Candidate

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The mass $m_{\eta_c}$ and total width $\Gamma_{\rm tot}^{\eta_c}$ of the $\eta_c$ meson have been measured in two-photon interactions at the SLAC $e^+e^-$ asymmetric $B$ Factory with the *BABAR* detector. With a sample of approximately 2500 reconstructed $\eta_c \to K_S^0 K^\pm \pi^\mp$ decays in 88 fb$^{-1}$ of data, the results are $m_{\eta_c} = 2982.5 \pm 1.1(\text{stat}) \pm 0.9(\text{syst})\ \text{MeV}/c^2$ and $\Gamma_{\rm tot}^{\eta_c} = 34.3 \pm 2.3(\text{stat}) \pm 0.9(\text{syst})\ \text{MeV}/c^2$. Using the same decay mode, a second resonance with $112 \pm 24$ events is observed with a mass of $3630.8 \pm 3.4(\text{stat}) \pm 1.0(\text{syst})\ \text{MeV}/c^2$ and width of $17.0 \pm 8.3(\text{stat}) \pm 2.5(\text{syst})\ \text{MeV}/c^2$. This observation is consistent with expectations for the $\eta_c(2S)$ state.

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The mass and width of the $\eta_c$ meson ($J^{PC} = 0^{-+}$), the lowest lying state of charmonium, are not as well-established as those of the $J/\psi$ meson. The world average [1] of the total width is $\Gamma_{\rm tot}^{\eta_c} = 16.0^{+3.6}_{-3.2}$ MeV/$c^2$, with individual measurements ranging from 7 to 27 MeV/$c^2$ with large errors. Recent measurements [2] extend from 17 to 29 MeV/$c^2$.

A radial excitation of the $\eta_c$, the $\eta_c(2S)$ state, is predicted by heavy quark potential models to lie below the $D\bar{D}$ threshold [3]. The hyperfine separations ($\eta_c$, $J/\psi$) and [$\eta_c(2S)$, $\psi(2S)$] are directly related to the spin-spin interaction. These calculations predict the mass splitting $m_{\psi(2S)} - m_{\eta_c(2S)}$ to be in the range 42–103 MeV/$c^2$. The Crystal Ball Collaboration [4] observed a peak at $91 \pm 5$ MeV, in the inclusive photon spectrum of $\psi(2S)$ decays, with a width $\Gamma \leq 8$ MeV (95% confidence level). This peak was considered most likely to be due to $\psi(2S) \to \eta_c(2S)\gamma$, with the $\eta_c(2S)$ state having a mass of $3594 \pm 5$ MeV/$c^2$. The Belle Collaboration recently reported signals attributed to the $\eta_c(2S)$ state, but with substantially higher masses: for the $K_S^0 K^- \pi^+$ mass distribution in exclusive $B \to K K_S^0 K^- \pi^+$ decays [5], they measured $3654 \pm 6(\text{stat}) \pm 8(\text{syst})$ MeV/$c^2$ and $\Gamma \leq 55$ MeV/$c^2$ (90% confidence level); from a signal observed in the inclusive $J/\psi$ spectrum in $e^+e^-$ annihilation [6], they measured $3622 \pm 12$ MeV/$c^2$. This state was unsuccessfully searched for in $p\bar{p} \to X \to \gamma\gamma$ [7] and $\gamma\gamma \to$ hadrons [8]. However, an estimate [9] of the two-photon production rate of the $\eta_c(2S)$ suggested that this meson could be identified in the current $e^+e^-$ $B$ Factories.

In this analysis we measure the masses and widths of the $\eta_c$ and of a state interpreted as the $\eta_c(2S)$ meson, by reconstructing $\gamma\gamma \to X \to K_S^0 K^\pm \pi^\mp$ ($K_S^0 \to \pi^+\pi^-$) events in the *BABAR* detector at the PEP-II energy-asymmetric $e^+e^-$ storage ring at SLAC. The data sample was collected both on and slightly below the $\Upsilon(4S)$ resonance, and corresponds to an integrated luminosity of 88 fb$^{-1}$.

The *BABAR* detector is described in detail in Ref. [10]. The momenta of charged particles are measured and their trajectories reconstructed with two detector systems located in a 1.5 T solenoidal magnetic field: a five-layer, double-sided silicon strip vertex tracker and a 40-layer drift chamber. Both devices provide $dE/dx$ measurement. Charged particle identification is provided by a detector of internally reflected Cherenkov light, complemented by the $dE/dx$ measurement. The energies of electrons and photons are measured in a calorimeter consisting of 6580 CsI(Tl) crystals.

The mesons are formed by the interaction of two virtual photons. Since the $e^+$ and $e^-$ scatter through too small an angle to be detected, the two photons are quasireal and nearly aligned with the incident beams. A preselected sample comprises events having four charged tracks with a net zero charge and with total laboratory energy less than 9 GeV. This removes most events coming from $B$ meson decays.

A further selection of events is aimed at maximizing the ratio $S/\sqrt{(S+B)}$, where $S$ is the signal and $B$ the background, both taken within a $\pm 50$ MeV/$c^2$ window around the $\eta_c$ peak. Events with total transverse momentum in the center of mass greater than 1.05 GeV/$c$ or with total energy of neutral particles greater than 0.7 GeV are rejected. In order to identify $\eta_c \to K_S^0 K^\pm \pi^\mp$ events, decays with one $K_S^0 \to \pi^+\pi^-$ candidate that lies within the window $0.482 \leq M(K_S^0) \leq 0.512$ GeV/$c^2$ are selected. Of the two remaining tracks, we require that one and only one be identified as a kaon; the other one is assumed to be a pion. The angle between the $K_S^0$ momentum and its flight path, as determined by the $K_S^0$ and $K^\pm\pi^\mp$ vertices, is required to be small ($\cos\theta(K_S^0) \geq 0.992$). Finally, the $K_S^0 K^\pm \pi^\mp$ vertex is fitted, with the $K_S^0$ mass constrained to the world average value [1].

The resulting $K_S^0 K^\pm \pi^\mp$ mass spectrum is shown in Fig. 1, with a large peak at the $\eta_c$ mass and a smaller peak at the $J/\psi$ mass. Although the $J/\psi$ cannot be produced in two-photon fusion, it is expected to be produced with hard photon emission by initial state radiation (ISR). The boost of the asymmetric collider brings the decay products of $J/\psi$ mesons traveling in the backward direction into the acceptance of the detector.

A thorough understanding of the experimental resolution is essential to determine the width of the $\eta_c$ meson. The resolution for the $J/\psi$ can be inferred from data since its natural width is negligible. This is not the case for the $\eta_c$, which has a natural width somewhat larger than the detector resolution. To help determine the resolution for the $\eta_c$, Monte Carlo calculations were performed. The generator [11] used to simulate $\gamma\gamma \to \eta_c \to K_S^0 K^\pm \pi^\mp$ events applies the formalism of Budnev *et al.* [12] to calculate the cross section for the process $e^+e^- \to e^+e^-\gamma\gamma \to e^+e^-\eta_c$. Monte Carlo calculations were also performed to generate $J/\psi$ events produced in $e^+e^-$

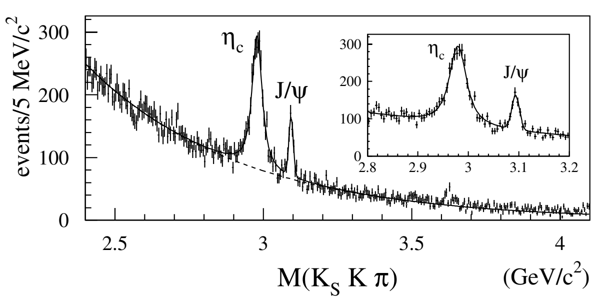


FIG. 1. The ($K_S^0 K^\pm \pi^\mp$) mass spectrum fitted (solid line) to $\eta_c + J/\psi +$ background, as explained in the text. The dashed line shows the background component of this fit. Inlaid is a magnified view of the region of the $\eta_c$ and $J/\psi$ peaks.

annihilation with initial state radiation. Both $\eta_c$ and $J/\psi$ were assumed to decay into $K_S^0 K^\pm \pi^\mp$ with a phase-space distribution. In the Monte Carlo simulation, the reconstructed $\eta_c$ and $J/\psi$ masses are both shifted by $-1.1\ \mathrm{MeV}/c^2$ (with statistical errors of 0.1 and $0.2\ \mathrm{MeV}/c^2$, respectively) from their generated values. This bias does not affect the mass difference $m_{J/\psi} - m_{\eta_c}$. The mass resolution is estimated by fitting the distribution of the difference between reconstructed mass and generated mass to a Gaussian function. Its standard deviation is found to be $7.3 \pm 0.1\ \mathrm{MeV}/c^2$ for the $\eta_c$ and $8.1 \pm 0.2\ \mathrm{MeV}/c^2$ for the $J/\psi$.

To determine the mass and width of the $\eta_c$, an unbinned maximum likelihood fit to the $K_S^0 K^\pm \pi^\mp$ mass spectrum for masses between 2.5 and $3.5\ \mathrm{GeV}/c^2$ is performed. The $\eta_c$ is represented by a Breit-Wigner function $(\Gamma/2)^2/[(W - m_{\eta_c})^2 + (\Gamma/2)^2]$, with $W$ the invariant $K_S^0 K^\pm \pi^\mp$ mass, convolved with a Gaussian resolution function. The $J/\psi$ peak is fitted with a Gaussian function. The background is represented by an exponential function of $W$, $A\exp(-\lambda W)$. The free parameters of the fits are the $J/\psi$ mass $m_{J/\psi}$, the mass difference $m_{J/\psi} - m_{\eta_c}$, the $\eta_c$ width $\Gamma_{\rm tot}^{\eta_c}$, the $J/\psi$ resolution $\sigma_{J/\psi}$, the coefficients $A$ and $\lambda$ of the background, and the numbers of events in the $\eta_c$ and $J/\psi$ peaks. The resolution $\sigma_{\eta_c}$ of the $\eta_c$ peak is constrained to a value $0.8\ \mathrm{MeV}/c^2$ lower than the $J/\psi$ resolution, as indicated by the Monte Carlo simulation. The results of the fit are $m_{J/\psi} = 3093.6 \pm 0.8\ \mathrm{MeV}/c^2$, $m_{J/\psi} - m_{\eta_c} = 114.4 \pm 1.1\ \mathrm{MeV}/c^2$, $\sigma_{J/\psi} = 7.6 \pm 0.8\ \mathrm{MeV}/c^2$, $\Gamma_{\rm tot}^{\eta_c} = 34.3 \pm 2.3\ \mathrm{MeV}/c^2$. The numbers of $\eta_c$ and $J/\psi$ events are, respectively, $2547 \pm 90$ and $358 \pm 33$.

The mass resolution found for the $J/\psi$ is $0.5 \pm 0.8\ \mathrm{MeV}/c^2$ lower than the Monte Carlo prediction, but consistent with it. To evaluate the systematic uncertainty affecting the $\eta_c$ width, the conditions of the fit are varied as shown in Table I. When $\sigma_{J/\psi}$ and $\sigma_{\eta_c}$ are fixed to the values obtained in the Monte Carlo simulation (second row of Table I), the width of the $\eta_c$ changes by $0.6\ \mathrm{MeV}/c^2$. We take this value as an estimate of the systematic uncertainty associated with the uncertainty on the $\eta_c$ resolution. The value of $\Gamma_{\rm tot}^{\eta_c}$ changes by $0.4\ \mathrm{MeV}/c^2$ on average when the mass range of the fit is varied from 2.4–3.6 $\mathrm{GeV}/c^2$ to 2.7–3.3 $\mathrm{GeV}/c^2$. This gives an estimate of the systematic uncertainty associated with the choice of the mass range of the fit. By varying the event selection parameters, we estimate that the systematic uncertainty associated with the event selection is $0.5\ \mathrm{MeV}/c^2$. The total systematic uncertainty on the $\eta_c$ width is then $0.9\ \mathrm{MeV}/c^2$. The final value of the $\eta_c$ width is

$$\Gamma_{\rm tot}^{\eta_c} = 34.3 \pm 2.3(\mathrm{stat}) \pm 0.9(\mathrm{syst})\ \mathrm{MeV}/c^2.$$

The $\eta_c$ mass is $2982.5 \pm 1.1(\mathrm{stat})\ \mathrm{MeV}/c^2$, obtained by subtracting $114.4\ \mathrm{MeV}/c^2$ from the current world average value of the $J/\psi$ mass [1]. The $\eta_c$ and $J/\psi$ masses are unchanged by the alternative fits listed in Table I. We estimate that the systematic uncertainty on $m_{J/\psi} - m_{\eta_c}$, associated with the event selection, is $0.8\ \mathrm{MeV}/c^2$. After correction for the $-1.1\ \mathrm{MeV}/c^2$ shift seen in simulation, as mentioned above, the $J/\psi$ mass is still shifted by an additional $-2.2\ \mathrm{MeV}/c^2$ relative to the well-established world average value [1]. Because $J/\psi$ events and $\eta_c$ events populate different regions of detector acceptance, as illustrated in Fig. 2 for final-state pions, a shift that applies to the $J/\psi$ may not entirely apply to the $\eta_c$ due to possible imperfections in the detector modeling. When one selects $\eta_c$ events with decay particles going backward, as is the case for the $J/\psi$, the $\eta_c$ peak shifts by $0.5\ \mathrm{MeV}/c^2$, which we take as a contribution to the systematic uncertainty. The final value of the $\eta_c$ mass is then

$$m_{\eta_c} = 2982.5 \pm 1.1(\mathrm{stat}) \pm 0.9(\mathrm{syst})\ \mathrm{MeV}/c^2.$$

The peak at $3.63\ \mathrm{GeV}/c^2$ in the $K_S^0 K\pi$ mass spectrum (Fig. 1) may be the expected $\eta_c(2S)$ state. In order to optimize the significance of the signal, a new event selection is performed that maximizes the ratio $S/\sqrt{B}$. This is appropriate in place of $S/\sqrt{S+B}$ because we need to establish the significance of the peak without bias from

TABLE I. Results of unbinned maximum likelihood fits to the $\eta_c$ and $J/\psi$ mass spectra. The resolutions of the $J/\psi$ and $\eta_c$ peaks are, respectively, $\sigma_{J/\psi}$ and $\sigma_{\eta_c}$. The first row presents the nominal fit, and the succeeding rows are used for systematic studies of the $\eta_c$ width. MC denotes results of Monte Carlo simulations.

| Mass range $\mathrm{MeV}/c^2$ | $\Gamma_{\rm tot}^{\eta_c}$ $\mathrm{MeV}/c^2$ | $\sigma_{J/\psi}$ $\mathrm{MeV}/c^2$ | $\sigma_{\eta_c}$ $\mathrm{MeV}/c^2$ |
|---|---|---|---|
| 2.5–3.5 | $34.3 \pm 2.3$ | $7.6 \pm 0.8$ | $\sigma_{J/\psi} - 0.8$ |
| 2.5–3.5 | $33.7 \pm 2.0$ | 8.1 (MC) | 7.3 (MC) |
| 2.4–3.6 | $33.7 \pm 2.3$ | $7.6 \pm 0.8$ | $\sigma_{J/\psi} - 0.8$ |
| 2.6–3.4 | $34.4 \pm 2.3$ | $7.7 \pm 0.9$ | $\sigma_{J/\psi} - 0.8$ |
| 2.7–3.3 | $34.7 \pm 2.4$ | $7.7 \pm 0.8$ | $\sigma_{J/\psi} - 0.8$ |

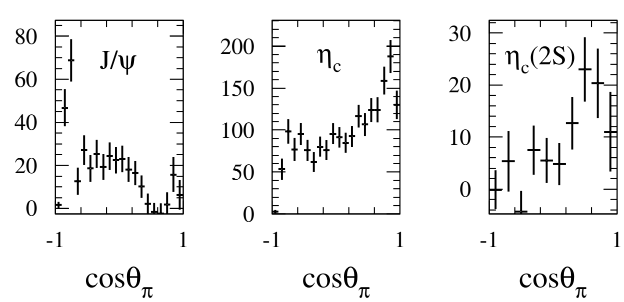


FIG. 2. Angular distributions of pions from the decays of $J/\psi$, $\eta_c$, and $\eta_c(2S)$, in the laboratory frame ($\Theta_\pi$ is the pion polar angle). The backgrounds determined from sidebands have been subtracted.

assumptions about how much signal to expect, and in any case the branching fraction and $\gamma\gamma$ width needed for such a prediction are unknown. For $S$, we take the signal as generated from Monte Carlo simulation and $B$ is the background estimated from the average of the $\eta_c(2S)$ sidebands 3.30–3.48 GeV$/c^2$ and 3.78–3.96 GeV$/c^2$ of the data. The optimized selection is the same as for the $\eta_c$, with two exceptions: The total energy deposited by neutral particles is required to be less than 0.25 GeV and we require $\cos\theta(K_S^0) \geq 0.995$. The resulting mass spectrum is shown in Fig. 3.

The mass resolution determined from the Monte Carlo simulation is 9.2 MeV$/c^2$ and the reconstructed mass is 0.4 MeV$/c^2$ lower than the generated mass. Since the resolution for the $J/\psi$ was found to be $0.5 \pm 0.8$ MeV$/c^2$ lower in the data than in the Monte Carlo simulation, we assume that the resolution for $\eta_c(2S)$ is also 0.5 MeV$/c^2$ lower in the data, with an uncertainty of 0.8 MeV$/c^2$. The $K_S^0K^\pm\pi^\mp$ mass spectrum is then fitted between 3.3 and 4.0 GeV$/c^2$, the $\eta_c(2S)$ resonance shape being represented by a Breit-Wigner function convolved with a Gaussian resolution function with standard deviation 8.7 MeV$/c^2$. The background is fitted with an exponential shape. The fit results in $112 \pm 24$ events in the $\eta_c(2S)$ peak. The significance of this signal is characterized by the quantity $\sqrt{2 \times \log\mathcal{L}_{\max}/\mathcal{L}_0} = 4.9$, where $\mathcal{L}_{\max}$ and $\mathcal{L}_0$ are, respectively, the likelihoods for the fits with and without the $\eta_c(2S)$ peak.

The $m_{\eta_c(2S)} - m_{J/\psi}$ mass difference is found to be $534.6 \pm 3.4$(stat) MeV$/c^2$. Taking into account the shifts from generated to reconstructed masses of $-1.1$ MeV$/c^2$ for the $J/\psi$ and $-0.4$ MeV$/c^2$ for the $\eta_c(2S)$, as found in the Monte Carlo simulation, this mass difference becomes 533.9 MeV$/c^2$. The $\eta_c(2S)$ mass is then $m_{\eta_c(2S)} = m_{J/\psi} + 533.9 = 3630.8 \pm 3.4$(stat) MeV$/c^2$. The measured total width is $17.0 \pm 8.3$(stat) MeV$/c^2$. The resolution uncertainty of 0.8 MeV$/c^2$ results in a systematic uncertainty of 0.1 MeV$/c^2$ on the $\eta_c(2S)$ mass and 2.0 MeV$/c^2$ on its total width. When the mass range for the fit is varied to 3.2–4.1 or 3.4–3.9 GeV$/c^2$, the $\eta_c(2S)$ mass varies by 0.2 MeV$/c^2$, whereas its width varies by 1.2 MeV$/c^2$ on average. The 0.5 MeV$/c^2$ uncertainty on the $-2.2$ MeV$/c^2$ shift observed for the measured $J/\psi$ mass relative to the world average value is taken as a systematic uncertainty on the $\eta_c(2S)$ mass. Based on the upper limit for the branching fraction $\psi(2S) \to K^+K^-\pi^0$ [1], and a theoretical estimate for ISR production predicting that $\psi(2S)$ is a factor of 14/36 below $J/\psi$ [13], we estimate that $\psi(2S)$ (with a mass of 3.686 GeV$/c^2$ [1]) could contribute up to five $K_S^0K^\pm\pi^\mp$ events to the spectrum of Fig. 3. Allowing for this reduces the $\eta_c(2S)$ width by 0.7 MeV, which we take as a systematic uncertainty, whereas the $\eta_c(2S)$ mass varies by about 0.1 MeV$/c^2$. The systematic uncertainties associated with the event selection are taken to be the same as for the $\eta_c$, 0.8 MeV$/c^2$ for the $\eta_c(2S)$ mass and 0.5 MeV$/c^2$ for its total width. Adding all systematic uncertainties in quadrature, the final results are

$$m_{\eta_c(2S)} = 3630.8 \pm 3.4(\text{stat}) \pm 1.0(\text{syst})\ \text{MeV}/c^2,$$
$$\Gamma_{\text{tot}}^{\eta_c(2S)} = 17.0 \pm 8.3(\text{stat}) \pm 2.5(\text{syst})\ \text{MeV}/c^2.$$

While we have not measured the quantum numbers of the state at 3630.8 MeV$/c^2$, demonstrating that it is formed from the fusion of two quasireal photons would at least restrict the possibilities. Such a process can occur only if $C = +$, and $J^P = 0^-$ ($0^+$ is excluded by the final state), $2^\pm$, $3^+$, $4^\pm$, .... Other combinations would be possible if production were via an ISR process, or if at least one of the two photons in two-photon fusion were highly virtual. However, ISR is excluded as the source, because the decay products of this state have angular distributions concentrated in the forward hemisphere, such as the $\eta_c$, in contrast to the $J/\psi$ for which the decay products peak in the backward direction. This is illustrated in Fig. 2. Moreover, the distribution of the total transverse momentum (Fig. 4) is peaked at 0, characteristic of quasireal photons, and this excludes spin-one

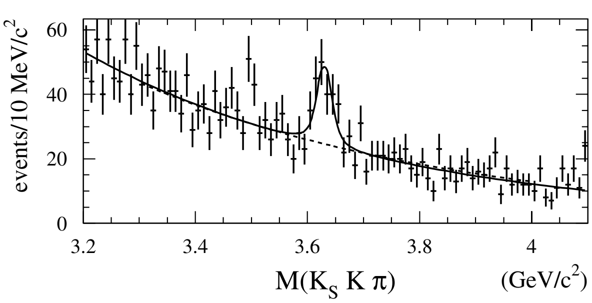


FIG. 3. The $K_S^0K^\pm\pi^\mp$ mass spectrum with event selection optimized for the $\eta_c(2S)$ as described in the text. The solid curve is the fit with the $\eta_c(2S)$ resonance shape being represented by a Breit-Wigner function convolved with a Gaussian resolution function. The dashed curve shows the background component of this fit.

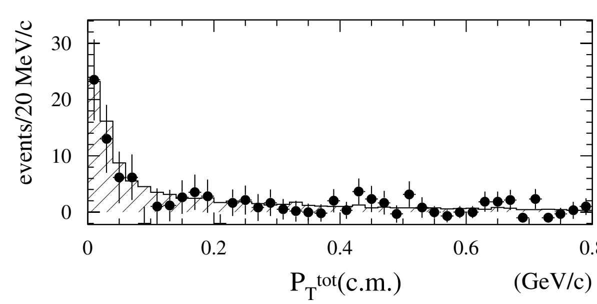


FIG. 4. Total transverse momentum in the center of mass. The hatched solid line is the result of the two-photon Monte Carlo simulation for the $\eta_c(2S)$ state, normalized to the data. The data are events in the 3.60–3.66 GeV$/c^2$ mass region; the background determined from mass sidebands 3.30–3.48 GeV$/c^2$ and 3.78–3.96 GeV$/c^2$ has been subtracted.

production. Thus, the evidence supports the state having quantum numbers $J^{PC} = 0^{-+}$ or $J \geq 2$. But $J \geq 2$ is disfavored for a charmonium state of such low mass, which suggests that the state has the quantum numbers of the $\eta_c(2S)$.

In summary, we have measured the mass difference between the $J/\psi$ and the $\eta_c$ and the total width of the $\eta_c$, using $2547 \pm 90$ events of $\gamma\gamma \to \eta_c \to K_S^0 K^\pm \pi^\mp$ and $358 \pm 33$ $J/\psi \to K_S^0 K^\pm \pi^\mp$ events, selected with the *BABAR* detector.

A state which could be the expected $\eta_c(2S)$ was also observed in the $K_S^0 K^\pm \pi^\mp$ decay mode, with $112 \pm 24$ events, and its mass and total width measured. The measured mass is significantly different from the mass of the state reported by the Crystal Ball Collaboration [4], but consistent with the measurements of the Belle Collaboration [5,6]. We have presented evidence that this state is produced via the fusion of two quasireal photons, which suggests that its quantum numbers are those of the $\eta_c(2S)$. The deduced mass splitting $m_{\psi(2S)} - m_{\eta_c(2S)} = 55.2 \pm 4.0\ \mathrm{MeV}/c^2$ is consistent with theoretical expectations.

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